4. SOURCE REDUCTION AND RECYCLING

This chapter presents estimates of GHG emissions and carbon sequestration resulting from source reduction and recycling of 15 manufactured materials: aluminum cans, steel cans, glass containers, plastic containers (LDPE, HDPE, and PET), corrugated boxes, magazines/third-class mail, newspaper, office paper, phonebooks, textbooks, dimensional lumber, medium-density fiberboard, and mixed paper.

To estimate GHG emissions associated with source reduction and recycling (and other MSW management options), we used a baseline scenario in which the material is manufactured from the current mix of virgin and recycled inputs, but has not yet been disposed of or recycled. Thus, the baseline for each material already incorporates some emissions from raw materials acquisition and manufacturing using the current mix of virgin and recycled inputs. Using this measurement convention, it follows that source reduction[1] reduces GHG emissions from the raw material acquisition and manufacturing phase of the life cycle for all materials. Moreover, source reduction of paper results in forest carbon sequestration (as discussed in Chapter 3).

Manufacturing from recycled inputs generally requires less energy, and thus lower GHG emissions, than manufacturing from virgin inputs. Our recycling analysis indicates that recycling reduces GHG emissions for each of the materials studied.

4.1 GHG IMPLICATIONS OF SOURCE REDUCTION

When a material is source reduced (i.e., less of the material is made), the GHG emissions associated with making the material and managing the post-consumer waste are avoided. As discussed above, under the measurement convention used in this analysis, source reduction has (1) negative raw material and manufacturing GHG emissions (i.e., it avoids baseline emissions attributable to current production); (2) forest carbon sequestration benefits for paper products (also treated as negative emissions, as estimated in Chapter 3); and (3) zero waste management GHG emissions. Exhibit 4-1 presents the GHG implications of source reduction. The values for forest carbon sequestration were copied from Exhibit 3-8.

In order to compare source reduction to other solid waste management alternatives, we compared the GHG reductions from source reduction to the life-cycle GHG emissions of another solid waste management option (e.g., landfilling). This approach enables policy makers to evaluate, on a per-ton basis, the overall difference in GHG emissions between (1) source reducing 1 ton of material and (2) manufacturing and then managing (post-consumer) 1 ton of the same material. Such comparisons are made in the Executive Summary and in Chapter 8 of this report. For most materials, source reduction has lower GHG emissions than the other waste management options.

[1] In this analysis, the values reported for source reduction apply to material lightweighting or extension of a product's useful life. We assume no substitution by another material or product, and thus we assume no offsetting GHG emissions from another material or product. Thus, the data do not directly indicate GHG effects of source reduction that involves material substitution. Considerations for estimating the GHG effects of material substitution are presented in Section 4.3 below.

Exhibit 4-1
GHG Emissions for Source Reduction
(MTCE/Ton of Material Source Reduced)

Material	Avoided GHG Emissions from Raw Materials Acquistion and Manufacturing			Changes in Forest Carbon Storage		Net Emissions	Net Emissions
	For Current Mix of Inputs	For 100% Virgin Inputs	Post-consumer	For Current Mix of Inputs	For 100% Virgin Inputs	For Current Mix of Inputs	For 100% Virgin Inputs
Aluminum Cans	-2.49	-4.67	0.00	0.00	0.00	-2.49	-4.67
Steel Cans	-0.79	-1.01	0.00	0.00	0.00	-0.79	-1.01
Glass	-0.14	-0.16	0.00	0.00	0.00	-0.14	-0.16
HDPE	-0.49	-0.53	0.00	0.00	0.00	-0.49	-0.53
LDPE	-0.61	-0.64	0.00	0.00	0.00	-0.61	-0.64
PET	-0.49	-0.58	0.00	0.00	0.00	-0.49	-0.58
Corrugated Cardboard	-0.24	-0.22	0.00	-0.28	-0.73	-0.51	-0.96
Magazines/Third-class Mail	-0.46	-0.46	0.00	-0.58	-0.73	-1.04	-1.19
Newspaper	-0.46	-0.59	0.00	-0.35	-0.73	-0.81	-1.32
Office Paper	-0.31	-0.28	0.00	-0.50	-0.73	-0.80	-1.01
Phonebooks	-0.64	-0.67	0.00	-0.65	-0.73	-1.28	-1.40
Textbooks	-0.59	-0.59	0.00	-0.64	-0.73	-1.23	-1.32
Dimensional Lumber	-0.05	-0.05	0.00	-0.50	-0.50	-0.55	-0.55
Medium-density Fiberboard	-0.10	-0.10	0.00	-0.50	-0.50	-0.60	-0.60
Mixed Paper							
Broad Definition	NA	NA	NA	NA	NA	NA	NA
Residential Definition	NA	NA	NA	NA	NA	NA	NA
Office Paper Definition	NA	NA	NA	NA	NA	NA	NA
Mixed MSW	NA	NA	NA	NA	NA	NA	NA

Note that totals may not add due to rounding, and more digits may be displayed than are significant.
NA: Not applicable, or in the case of composting of paper, not analyzed.

4.2 GHG IMPLICATIONS OF RECYCLING

When a material is recycled, it is used in place of virgin inputs in the manufacturing process, rather than being disposed of and managed as waste.[2] As with source reduction of paper products, recycling of paper also results in forest carbon sequestration.

Most of the materials considered in this analysis are modeled as being recycled in a closed loop (e.g., newspaper is recycled into new newspaper). However, several paper types are recycled in an open loop (i.e., they are recycled into more than one product) under the general heading of mixed paper.[3] Mixed paper is included because it is recycled in large quantities, and is an important class of scrap material in many recycling programs. However, presenting a single definition of mixed paper is difficult because each mill using recovered paper defines its own supply, which varies with the availability and price of different grades of paper.

For the purpose of this report, we identified three definitions for mixed paper: broad, office, and residential. To assist recyclers in determining which definition corresponds most closely to mixed paper streams they manage, the composition of each is presented in Exhibit 4-2. The broad definition of mixed paper includes almost all printing-writing paper, folding boxes, and most paper packaging. Mixed paper from offices includes copier and printer paper, stationary and envelopes, and commercial printing. The typical mix of papers from residential curbside pick-up includes high-grade office paper, magazines, catalogs, commercial printing, folding cartons, and a small amount of old corrugated containers. Mixed paper as characterized by the broad and residential definitions can be remanufactured via an open loop into recycled boxboard. Mixed paper from offices is typically used to manufacture commercial paper towels.

When any material is recovered for recycling, some portion of the recovered material is unsuitable for use as a recycled input. This portion is discarded either in the recovery stage or in the remanufacturing stage. Consequently, less than 1 ton of new material generally is made from 1 ton of recovered materials. Material losses are quantified and translated into loss rates. In this analysis, we used estimates of loss rates provided by Franklin Associates, Ltd. (FAL) for steel, dimensional lumber, and medium-density fiberboard (the same materials for which we used FAL's energy data, as described in Chapter 2). EPA's Office of Research and Development (ORD) provided loss rates for the other materials. These values are shown in Exhibit 4-3.

GHG emission reductions associated with remanufacture using recycled inputs are calculated by taking the difference between (1) the GHG emissions from manufacturing a material from 100 percent recycled inputs, and (2) the GHG emissions from manufacturing an equivalent amount of the material (accounting for loss rates) from 100 percent virgin inputs.

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[2] Note that when paper is manufactured from recycled inputs, the amount of paper sludge produced is greater than when paper is made from virgin inputs. This difference is because recycled paper has more short fibers, which must be screened out. We made a preliminary estimate of the GHG emissions from paper sludge managed in landfills; our results indicated that net GHG emissions (i.e., CH_4 emissions minus carbon sequestration) were close to zero. Because the emissions are small and highly uncertain, no quantitative estimate is included in this report.

[3] This report also includes estimates for mixed MSW, mixed plastics, mixed organics, and mixed recyclables, i.e., a mixture of the principal paper, metal, and plastic materials that are recycled. These other mixed materials are discussed in Chapter 8.

Exhibit 4-2
Summary of Mixed Paper Scenarios
(Composition as a percentage of total)

Paper Grade	All Paper and Paperboard in MSW (1)	Mixed Paper: Broad Definition (2)	Mixed Paper: Offices (3)	Mixed Paper: Single-Family Residential (4)
Uncoated groundwood paper	4.9%	4.9%	7.9%	2.2%
Coated free sheet paper	5.0%	12.0%	13.9%	11.5%
Coated groundwood paper	4.3%	11.5%	30.7%	17.7%
Uncoated free sheet paper	14.3%	37.6%	41.6%	18.4%
Cotton fiber paper	0.1%	0.4%	1.8%	0.2%
Bleached bristols	1.5%	3.9%	4.1%	2.8%
Newspaper	13.3%	2.9%		2.9%
Virgin corrugated boxes	29.6%			12.2%
Recycled corrugated boxes	6.8%			2.8%
Unbleached kraft folding boxes	1.5%	5.7%		4.1%
Bleached kraft folding boxes	2.8%	5.7%		5.8%
Recycled folding boxes	3.0%	7.9%		8.0%
Bleached bags and sacks	0.4%	1.0%		1.6%
Unbleached bags and sacks	2.1%	5.6%		9.0%
Unbleached wrapping paper	0.1%	0.2%		
Converting paper	0.3%			
Special industrial paper	1.3%			
Other paperboard	2.5%			
Paper plates and cups	1.2%			
Tissue, towels	3.9%			
Set-up boxes	0.3%	0.7%		0.6%
Other paper packaging	0.8%			
Totals	100.0%	100.0%	100.0%	100.0%

(1) All grades of paper and paperboard in MSW.
(2) Excludes newspaper, old corrugated containers, tissue produce, paper plates and cups, converting and special industrial papers, non-packaging paperboard such as album covers and posterboard, and paper labels.
(3) Includes the high-grade papers (ledger and computer printout) as well as stationery, mail, magazines, and manila folders. Could be recovered as "File Stock."
(4) Represents a typical collection of mixed paper from a single-family curbside program. Includes printing-writing papers, corrugated boxes, folding cartons, and bags and sacks.
Source: Working papers prepared by Franklin Associates, Ltd., October 1997.

Exhibit 4-3
Loss Rates For Recovered Materials

(a) Material	(b) Data Source	(c) Percent of Recovered Materials Retained in the Recovery Stage	(d) Product Made per Ton of Recycled Inputs In the Manufacturing Stage	(e) (e = c * d) Tons of Product Made Per Ton Recovered Materials
Aluminum Cans	FAL & ORD *	100	0.93	0.93
Steel Cans	FAL	100	0.98	0.98
Glass	FAL & ORD *	90	0.98	0.88
HDPE	FAL & ORD *	90	0.86	0.78
LDPE	FAL & ORD *	90	0.86	0.78
PET	FAL & ORD *	90	0.86	0.78
Corrugated Cardboard	FAL & ORD *	100	0.93	0.93
Magazines/Third-class Mail	FAL & ORD *	95	0.71	0.67
Newspaper	FAL & ORD *	95	0.94	0.90
Office Paper	FAL & ORD *	91	0.66	0.60
Phonebooks	FAL & ORD *	95	0.71	0.68
Textbooks	FAL & ORD *	95	0.69	0.66
Dimensional Lumber	FAL	88	0.91	0.80
Medium-density Fiberboard	FAL	88	0.91	0.80

* FAL provided data for column (c), while ORD provided data for column (d).

Explanatory notes: The value in column "b" accounts for losses such as recovered newspapers that were unsuitable for recycling because they were too wet. Column "c" reflects process waste losses at the manufacturing plant or mill. Column "d" is the product of the values in Columns "b" and "c."

The results of our analysis are shown in Exhibit 4-4. In this exhibit, for each material we present the differences between manufacture from virgin and recycled inputs for (1) energy-related GHG emissions (both in manufacturing processes and transportation), (2) process non-energy-related GHG emissions, and (3) forest carbon sequestration. Our method of accounting for loss rates yields estimates of GHG emissions on the basis of metric tons of carbon equivalent (MTCE) per short ton of material *collected for recycling* (rather than emissions per ton of material *made with recycled inputs*).

We recognize that some readers may find it more useful to evaluate recycling in terms of tons of recyclables *as marketed* rather than tons of materials *collected*. To adjust the emission factors reported in Exhibit 4-4 for that purpose, one would scale up the recycled input credits shown in columns "b" and "d" of that exhibit by the ratio of manufacturing loss rate to total loss rate (i.e., Exhibit 4-3 column "c" divided by column "d").

Another way that recycling projects can be measured is in terms of changes in recycled content of products. To evaluate the effects of such projects, one could use the following algorithm:[4]

[4] This approach would apply only where the products with recycled content involve the same "recycling loop" as the ones on which the values in this report are based (e.g., aluminum cans are recycled in a closed loop into more aluminum cans).

$T_{recyc} = T_{prod}*(RC_p-RC_i)/L$, where

T_{recyc} = tons of material recycled, as collected

T_{prod} = tons of the product with recycled content

RC_p = recycled content (in percent) after implementation of the project

RC_I = recycled content (in percent) initially

L = loss rate (from Exhibit 4-3, column "d")

Then, one could use the emission factors in this report directly with the tons of material recycled (as collected) to estimate GHG emissions.

In order to compare GHG emissions from recycling to those attributable to another solid waste management option such as landfilling, we compared the total GHG emissions from recycling the material to the GHG emissions from managing the disposal of the same material under another waste management option. The baseline for a given material (which includes GHG emissions from raw materials acquisition and manufacturing for the current mix of virgin and recycled inputs) for both options is the same. Overall, because recycling reduces the amount of energy required to manufacture materials (as compared to manufacture with virgin inputs) and leads to avoided process non-energy GHG emissions, recycling has lower GHG emissions than all other waste management options except for source reduction.

4.3 SOURCE REDUCTION WITH MATERIAL SUBSTITUTION

As noted above, our analysis of source reduction is based on an assumption that source reduction is achieved by practices such as lightweighting, double-sided copying, and material reuse. However, it is also possible to source reduce one type of material by substituting another material. Analyzing the GHG impacts of this type of source reduction becomes more complicated. Essentially, one would need to estimate the *net* GHG impacts of (1) source reduction of the original material, and (2) manufacture of the substitute material and its disposal fate. A quantitative analysis of source reduction with material substitution was beyond the scope of this report because of the large number of materials that could be substituted for the materials analyzed in this report (including composite materials, e.g., a composite of paper and plastic used in juice boxes), and the need for application-specific data. Where both the original material and the substitute material are addressed in this report, however, the GHG impacts of source reduction with material substitution may be estimated.

The estimate would be based on (1) the data provided in this report for the material that is source reduced; (2) the mass substitution rate for the material that is substituted; and (3) data in this report for the material substituted. The mass substitution rate is the number of tons of substitute material used per ton of original material source reduced. Note, however, that in calculating the mass substitution rate, one should account for any difference in the number of times that a product made from the original material is used prior to waste management, compared to the number of times a product made from the substitute material will be used prior to waste management.

To estimate the GHG impacts of source reduction with material substitution (per ton of material source reduced), one should consider the following: a specific baseline scenario, including waste management; an alternative scenario, involving the substitute material and a waste management method; the number of tons of material used in each scenario, using the mass substitution rate; the net GHG emissions for the baseline; the GHG impacts of source reduction of the original material; the GHG impacts of manufacturing the substitute material; and the GHG impacts of waste management for the substitute material. Among other factors, these considerations will allow for a comparison of net GHG emissions from source reduction with material substitution to the baseline.

4.4 LIMITATIONS

Because the data presented in this chapter were developed earlier in Chapters 2 and 3, the limitations discussed in those chapters also apply to the values presented here. Five other limitations are as follows:

- There may be GHG impacts from disposal of industrial wastes, particularly paper sludge at paper mills. Because of the complexity of analyzing these second-order effects and the lack of data, we did not include them in our estimates. We did perform a screening analysis for paper sludge, however, based on (1) data on sludge generation rates and sludge composition (i.e., percentage of cellulose, hemicellulose, lignin, etc. in sludge),[5] and (2) professional judgment on the CH_4 generation rates for cellulose, etc. The screening analysis indicated that net GHG emissions (CH_4 emissions minus carbon storage) from paper sludge are probably on the order of 0.00 MTCE per ton of paper made from virgin inputs to 0.01 MTCE per ton for recycled inputs. Our worst case bounding assumptions indicated maximum possible net GHG emissions ranging from 0.03 to 0.11 MTCE per ton of paper (depending on the type of paper and whether virgin or recycled inputs are used).
- The recycling results are reported in terms of GHG emissions per ton of material collected for recycling. Thus, the emission factors incorporate assumptions on loss of material through collection, sorting, and remanufacturing. There is uncertainty in the loss rates: some materials recovery facilities and manufacturing processes may recover or use recycled materials more or less efficiently than estimated here.
- The models used to evaluate forest carbon sequestration and those used to evaluate energy and non-energy emissions differ in their methods for accounting for loss rates. Although one can directly adjust the emission factors reported here for process emissions so that they apply to tons of materials as marketed (rather than tons as collected), there is no straightforward way to adjust the forest carbon estimate.
- Because our modeling approach assumes closed-loop recycling for all materials except mixed paper, it does not fully reflect the prevalence and diversity of open-loop recycling. Most of the materials in our analysis are recycled into a variety of manufactured products, not just into the original material. Resource limitations prevent an exhaustive analysis of all the recycling possibilities for each of the materials analyzed.
- For the purpose of simplicity, we assumed that increased recycling does not change overall demand for products. In other words, we assumed that each incremental ton of recycled inputs would displace virgin inputs in the manufacturing sector. In reality, there may be a relationship between recycling and demand for products with recycled content, since these products become cheaper as the supply of recycled materials increases.

[5] ICF Consulting. 1996. Memorandum to EPA Office of Solid Waste, “Methane Generation from Paper Sludge,” December.

Exhibit 4-4
GHG Emissions for Recycling
(MTCE/Ton of Material Recovered)

(a) Material	(b) Recycled Input Credit*: Process Energy	(c) Recycled Input Credit*: Transportation Energy	(d) Recycled Input Credit*: Process Non-Energy	(e) Forest Carbon Sequestration	(f) (f = b + c + d + e) GHG Reductions From Using Recycled Inputs Instead of Virgin Inputs
Aluminum Cans	-2.92	-0.14	-1.05	0.00	-4.11
Steel Cans	-0.48	-0.01	0.00	0.00	-0.49
Glass	-0.03	0.00	-0.04	0.00	-0.08
HDPE	-0.34	0.00	-0.04	0.00	-0.38
LDPE	-0.43	0.00	-0.04	0.00	-0.47
PET	-0.40	0.00	-0.02	0.00	-0.42
Corrugated Cardboard	0.04	-0.01	0.00	-0.73	-0.71
Magazines/Third-class Mail	0.00	0.00	0.00	-0.73	-0.74
Newspaper	-0.21	-0.01	0.00	-0.73	-0.95
Office Paper	0.06	0.00	0.00	-0.73	-0.68
Phonebooks	-0.18	0.00	0.00	-0.73	-0.91
Textbooks	-0.01	0.00	0.00	-0.73	-0.75
Dimensional Lumber	0.02	0.00	0.00	-0.69	-0.67
Medium-density Fiberboard	0.01	0.00	0.00	-0.69	-0.67
Mixed Paper					
Broad Definition	0.08	-0.02	0.00	-0.73	-0.67
Residential Definition	0.08	-0.02	0.00	-0.73	-0.67
Office Paper Definition	-0.08	-0.02	0.00	-0.73	-0.83

Note that totals may not add due to rounding, and more digits may be displayed than are significant.

*Material that is recycled after use is then substituted for virgin inputs in the production of new products. This credit represents the difference in emissions that results from using recycled inputs rather than virgin inputs. The credit accounts for loss rates in collection, processing, and remanufacturing. Recycling credit is based on a weighted average of closed- and open-loop recycling for mixed paper. All other estimates are for closed-loop recycling.

Explanatory notes for Exhibit 4-4: Columns "b" and "c" show the reduction in process energy GHGs and transportation energy GHGs from making each material from recycled inputs, rather than virgin inputs. The values in columns "b" and "c" are based on (1) the difference in energy-related GHG emissions between making 1 ton of the material from 100% virgin inputs and from 100% recycled inputs, multiplied by (2) the estimated tons of material manufactured from 1 ton of material recovered, after accounting for loss rates in the recovery and remanufacturing stages. We first estimated the values in columns "b" and "c" based on data provided by FAL and ORD, as shown in Exhibits 2-2 through 2-5. Note that for two of the mixed paper definitions, the process energy GHG emissions are higher when using recycled inputs than when using virgin inputs (as shown by positive values in column "b"). This differemce is because the manufacture of boxboard (the product of open-loop recycling of these types of mixed paper) from virgin inputs uses a high proportion of biomass fuels, and the biogenic CO_2 emissions from biomass fuels are not counted as GHG emissions (see the discussion of biogenic CO_2 emissions in Chapter 1). Still, because of forest carbon sequestration, the net GHG emissions from recycling these two mixed paper definitions are negative.

For column "d, " which presents the process non-energy GHG emissions from recycling, we used (1) data showing the difference in process non-energy GHG emissions between making 1 ton of the material from 100% virgin inputs and from 100% recycled inputs (as shown in the second-to-last column of Exhibits 2-2 and 2-4) multiplied by (2) the estimated amount of material manufactured (in tons) from 1 ton of material recovered, after accounting for loss rates in the recovery and remanufacturing steps.

Next, column "e " shows the estimated forest carbon sequestration from recycling of paper products, as estimated in Chapter 3. The last column (column "f") sums columns "b" through "e" to show the GHG implications of recycling each material.

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